Detailed Analysis of the Thermal Mass Credits in a Code-Traceable DOE-2 Simulation of the 2001 IECC for a Single-Family Residence in Texas

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ABSTRACT

This paper presents the results of a study that investigates the thermal mass credits in the 2001 International Energy Conservation Code[1] (IECC) (ICC 1999, 2001) for a single-family residence in Texas using the DOE-2 building energy simulation program[2]. In this analysis seven different wall types were simulated, and each wall type was matched to the recommended overall U-value of a lightweight wall that meets the prescriptive specifications of the 2001 IECC. This paper presents an analysis of the total annual cooling and heating energy use for wall types with varying thermal mass, and thermostat settings, as well as recommendations concerning the most energy-efficient wall type, and includes input specification methods using the DOE-2 program.

BACKGROUND

Several authors have studied thermal mass issues in recent years. Kossecka and Kośny (1998) analyzed six typical wall configurations that have different arrangements of concrete and insulation layers to investigate the effect of wall material configuration on thermal stability of the building. In their study the DOE-2.1e program was used for the energy analysis of a one-story and slab on grade residential building for six different U.S. climates. They showed that walls with large amounts of thermal mass on the inner side, in good thermal contact with the interior of a building, showed the best thermal performance.

In another study Christian (1991) performed an analysis for the Council of American Building Officials' Model Energy Code Committee (CABO MEC) to develop exterior thermal mass credits (i.e., for heat capacity greater than or equal to 6 Btu/ft^2-ºF) that allowed for the creation of thermal mass credit tables for builders according to thermal mass located on the inside or the outside of the insulation and an integral case. In this study he analyzed thermal performance measurements from 14 test houses in two locations[3] with varying amounts of external wall mass, including wood-frame, masonry, adobe and wooden logs, and performed simulations of the test houses. He concluded that although the MEC thermal mass credit table may not be the most accurate values to be used for all typical conditions, in general, the experiments, simulation data, and MEC thermal mass credit tables showed that insulation placed on the outside of the thermal mass was best for most climates. Both of these studies provided a background for this study, which seeks to evaluate the thermal mass effects of different wall types based on the 2001 IECC for a residence built in Houston, Texas.

Winkelmann (1998) reported corrections and bug fixes in calculating the heat transfer through underground surfaces in DOE-2.1e. Since the program calculates the thermal mass of the underground surfaces according to custom weighting factors (CWFs) by multiplying the U-value with the surface area, and the temperature differences between zone temperature and ground temperature, the results of heat transfer are grossly overcalculated. Therefore, he suggested the use of U-EFFECTIVE and a procedure for defining the underground surface construction using a perimeter conduction factor. The simulations of this article applied Winkelmann's (1998) floor model for a slab-on-grade.

The DOE-2 program and its derivatives (i.e., EQUEST, EnergyGauge, ResCheck) are the most widely used programs in the U.S. to simulate residential code compliance. Also, the simulation models from this resarch, created with the DOE-2 program, were then linked to the Laboratory's code compliant test suite and the US EPA's eGRID[4] to convert the energy savings to NOx emissions reduction.

[1] The 2001 IECC notation refers to the 2000 IECC as modified by the 2001 Supplement (ICC 1999; 2000).
[2] DOE-2.1e, Version 119

[3] These locations included the National Institute of Standards and Technology (NIST) in Maryland and a site in Santa Fe, New Mexico)
[4] eGRID is the EPA's Emissions and Generation Resource Integrated Database. This publicly available database can be

In the DOE-2 program there are two methods to specify wall, roof and floor construction: 1) the "quick" mode option, which uses U-values for the walls and roofs, a lumped thermal mass and pre-calculated ASHRAE weighting factors for the wall's thermal mass components, and 2) the delayed mode option which uses layered walls and roof construction and DOE-2's Custom Weighting Factors (CWFs) to calculate a more accurate heat transfer through the layered building components (LBNL 1993), and includes a proper accounting of buildings's thermal mass elements.

In the 2001 IECC the use of exterior wall thermal mass credits (i.e., for walls with a heat capacity greater than or equal to 6 Btu/ft^2-ºF) is allowed through the use of the thermal mass credit tables[5], which specify whether or not the thermal mass is located on the inside or the outside of the insulation, with respect to the exterior ambient conditions, and an integral case (Christian 1991). Using the thermal mass credit table in the 2001 IECC, if all other building parameters remain constant, the exterior wall thermal mass improves or maintains the thermal performance of building's walls by reducing the wall U-value. In the 2001 International Energy Conservation Code (IECC), which is based on the Model Energy Code (MEC) (CABO 1998), exterior walls that are constructed with high-mass materials having a heat-capacity greater than or equal to 6 Btu/ft^2-°F shall meet the equivalent U-value (Table 1) for a climate such as Houston (0-2000 HDD_{65}).

Table 1: Recommended Overall U-value (U_w) of High-mass Materials in the 2001 IECC.

Wood framed wall (U_w)	HDD_{65}: 0 – 2,000	
	Table 502.2.1.1.2 (1)	Table 502.2.1.1.2 (2)
U_w=0.08	Exterior insulation (U_w)	Interior insulation (U_w)
	U_w = 0.13	U_w = 0.09

Unfortunately, the 2001 IECC provides no substantive reference to verify the source of the values in the table, and no advice was provided about how the thermal mass should be treated in a simulation program such as DOE-2. Since thermal mass is an issue in new residential construction in Texas, an analysis was developed to test the thermal mass credits on a code-compliant residential simulation in Texas to better inform how to simulate different wall types.

For the analysis, several different wall types, thermal mass amounts and simulation methods were investigated including (Figure 1): 1) a quick mode analysis that uses U-values instead of layered materials (not shown), 2) a 2"x4", wood-framed wall with studs 16" O.C. with insulation between the studs[6], 3) a 3" facia brick wall with 2"x4" wood-framed studs 16" O.C. with insulation between the studs, 4) an 8" concrete block wall with perlite fill in the cells of the block and insulation between the block and the interior gypsum board, 5) an 8" concrete block wall with perlite and concrete fill[7] in the cells of the block and insulation between the block and the interior gypsum board, 6) an 8" concrete block wall with perlite fill in the cells of the block and insulation outside the block, covered by stucco, and 7) an 8" concrete block with perlite and concrete fill in the cells of the block and insulation outside the block, covered by stucco. All wall types were simulated with and without a thermostat setback[8].

METHODOLOGY

<u>Base-case House</u>

The base-case house model used for the DOE-2 input file used the 2001 IECC specifications for a single-family residence that has 2,487 ft^2 gross floor area. The version of the model[9] used for this analysis was developed by the Energy Systems Laboratory at Texas A&M University as part of the Texas Emission Reduction Plan (TERP) (Haberl et al. 2003a, 2003b, 2004a, 2004b, 2004c and 2004d). Houston was chosen as the building location for this

found at www.epa.gov/airmarkets/egrid/. The information in this table is from a special edition of the eGRID database, provided by Art Diem at the USEPA for the TECQ for use with Senate Bill 5.

[5] Table 502.1.1.2(1), Table 502.1.1.2(2), and Table 502.1.1.2(3), p. 78 in 2000/2001 International Energy Conservation Code (IECC)

[6] The simulation actually uses two different layer wall assemblies with a percent framing factor to accurately account for the studs, headers and the framing lumber in the wall

[7] According to the DOE-2 BDL Summary (LBNL, 1993), concrete block wall with perlite and concrete is filled and reinforced concrete core every 24 inches of wall length with the remaining cores filled with perlite insulation.

[8] According to Table 402.1.3.5 on 2000/2001 IECC, the heating and cooling thermostats shall have a 5ºF of set-back/set-up and 6 hours/day of set-back/set-up duration.

[9] The results in this paper used the SNGFAM2ST.INP version of the Laboratory's code compliant test suite.

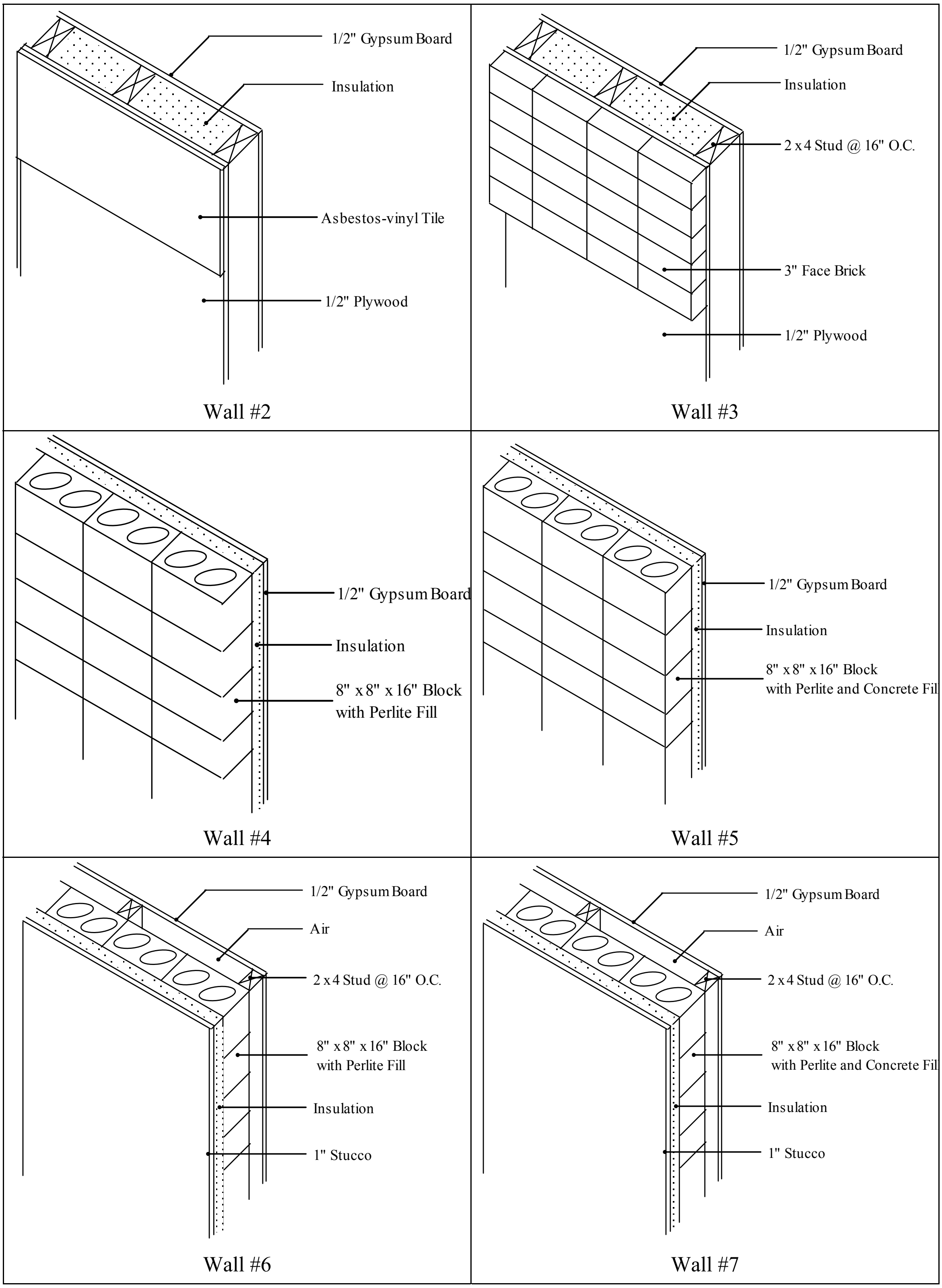
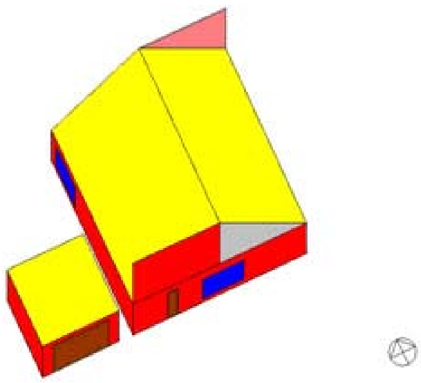


Figure 1: Thermal Mass Wall Types.

analysis and the TMY2 weather file for Houston was used to carry-out the simulations. The size of the base-case house for the simulation was an average house as specified by the National Association of Home Builders[10] (NAHB) with HVAC equipment efficiencies in compliance with the 2001 International Energy Conservation Code (IECC), which include SEER 10 and AFUE 0.78.

Figure 2 and Table 2 show the single-story, slab-on-grade simulation model of the base-case house. The non-triangular attic wall, used in the DOE-2 simulation, has an equivalent area of the triangular opening. Since it shows the same simulation results between the equivalent area of the triangular opening and proper triangle shape for the attic space, the rectangle shape which has an equivalent area is used for simplicity.

The simulation contains a duct model based on ASHRAE Standard 152 (ASHRAE 2004), which was created with a DOE-2 FUNCTION routine applied to the base-case house since DOE-2 does not adequately consider the heat gain or loss through the duct system to the attic (Kim 2006). The building is a single-story residence with 9 foot wall heights, and has wall and ceiling R-values of R-13 and R-26, respectively. The residence has a 15% window-to-wall ratio, with un-shaded windows distributed equally on all four sides that have a U-value of 0.75 and a SHGC of 0.4. The duct model assumed ducts that were in compliance with the 2001 IECC, which contained R-8 supply and R-4 return insulation levels over supply and return areas of 746 and 124 ft^2 respectively, which are based on ASHRAE Standard 152 (ASHRAE 2004).



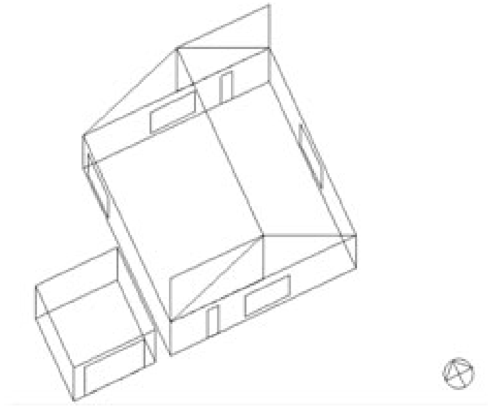


Figure 2: DrawBDL (Huang & Associates 2000) View of Base-case Model.

Table 2: Description of the House Used for the Analysis.

Item	Description	Notes
Location	Houston	
Climate Zone	IECC zone 4	HDD_{65}: 1500 – 1999
Floor Area (ft^2)	2478 ft^2	NAHB 2000
Wall Height (ft)	9 ft	NAHB 2000
Wall R-value	13	NAHB 2000
Ceiling R-value	26	NAHB 2000
Window to Wall Ratio	15%	2001 IECC
Glazing U-factor	0.75	2001 IECC
SHGC	0.4	2001 IECC
Duct Insulation	Supply duct: R-8, Return duct: R-4	2001 IECC
SEER	10	2001 IECC
AFUE (%)	0.78	2001 IECC
Supply duct surface area (ft^2)	746	ASHRAE Standard 152 – 2004
Return duct surface area (ft^2)	124	ASHRAE Standard 152 – 2004

Space Conditions

Table 3 shows the assumed space conditions for the 2001 IECC-compliant, DOE-2 simulation input file. Most values were taken from the 2001 IECC specifications in Chapters 4 and 5. For the sensible and latent heat gain from the occupants, Chapter 26 of the ASHRAE

[10] According to NAHB (2000), the average size of the house is 49.87 ft x 49.87 ft or 2,487ft^2

Handbook of Fundamentals (ASHRAE 2001) was used for the nominal heat gain values from occupants of 400 Btu/hr-person as shown (latent plus sensible). The air infiltration was calculated using ASHRAE Standard 136-1993, which yielded a value of 0.46 ACH for Houston. The floor weight in the quick run was set to match the required 11.5 lb/ft^2 [11]

Table 3: Space Conditions of the DOE-2 Input File.

Space Conditions on DOE-2 Input File	**Value**
TEMPERATURE	73ºF
NUMBER-OF-PEOPLE	2
PEOPLE-HG-LAT	200 Btu/hr
PEOPLE-HG-SENS	200 Btu/hr
LIGHTING-TYPE	INCAND
LIGHTING-KW[12]	0.44 kW
EQUIPMENT-KW[12]	0.44 kW
INF-METHOD	AIR-CHANGE
AIR-CHANGES/HR	0.46 (Houston)
FLOOR-WEIGHT	11.5 lb/ft^2

HVAC and DHW Systems

In order to simulate the HVAC system in the IECC-compliant run, the DOE-2 RESYS option was used. Table 4 shows the specifications used for the RESYS system simulation. Most values for the system simulation were taken from the 2001 IECC specification. The method to simulate the DHW energy used an Energy Factor (EF) based on the Building America performance analysis procedures (NREL 2001). For the DHW-EIR, the EF (Energy Factor=0.55) was calculated from the 2001 IECC, Table 504.2. Since the 2001 IECC requires a thermostat setback (6 hours setup and setback to 63°F from 68°F winter set-point temperature for heating and 83°F from 78°F summer set-point temperature for cooling from midnight to 6:00 A.M.), simulations for thermal mass effect analyses were performed using thermostat setback. In order to investigate the effects of thermostat setback, simulations without thermostat setback were also performed. All simulations have the same size cooling and heating system, and the system sizes were fixed according to the size of the house. For these simulations, the cooling system is 400ft^2/ton (6.2 tons or 74,610 Btu/hr) and the heating system is 1.8 times the size of the cooling system (134,299 Btu/hr).

Table 4: System Characteristics for the DOE-2 Input File.

Specification on DOE-2 Input File		**Default Value**
ZONE-CONTROL	DESIGN-HEAT-T	68 ºF
	DESIGN-COOL-T	78 ºF
	THROTTLING-RANGE	5 ºF
	THERMOSTAT-TYPE	PROPORTIONAL
SYSTEM-EQUIPMENT	COOLING-EIR	0.34
	FURNACE-HIR	1.25
SYSTEM	SYSTEM-TYPE	RESYS
	HEAT-SOURCE	GAS
PLANT-ASSIGNMENT	DHW-TYPE	GAS
	DHW-SUPPLY-T	120ºF
	DHW-EIR	1.83 (EF=0.55)
	DHW-SIZE	40 Gal
	DHW-GAL	0.027 Gal/min
	DHW-EIR-FPLR	NEWDHW

Quick and Delayed Construction Modes

The different construction types were analyzed to find the effect of high thermal mass materials in the IECC. Besides the base-case construction type, or quick mode, seven different wall types of thermal mass mode were investigated as shown in Table 5.

[11] This is on Chapter 402.1.3.3 (p.64) of the 2001 IECC, where two thermal mass factors are used in calculating annual energy performance: 1) Internal mass: 8 pounds per square foot, 2) Structural mass: 3.5 pounds per square foot.

[12] The sum of the LIGHTING-KW and EQUIPMENT-KW (i.e., 0.44 + 0.44 = 0.88 kW) were set to match the required 3,000 Btu/hr internal load required by Chapter 4 of the 2001 IECC.

Table 5: Summary of Wall Description of Each Simulation.

No	R-value hr- ft^2-°F/Btu	Uw Btu/ hr-ft^2-°F	Heat Capacity Btu/ft^2-°F	Insulation	Description	DOE-2 Calculation
1	13.0	0.076	N/A	N/A	Quick construction mode	Quick
2	13.0	0.077	4.39	Center	Asbestos-vinyl tile + Plywood + Insulation + Stud + Gypsum board	Delayed (CWFs)
3	11.0	0.091	8.05	Inside	3" Face Brick + Plywood + Insulation + Gypsum board	Delayed (CWFs)
4	11.1	0.090	7.94	Inside	8" Block with perlite filled + Insulation + Gypsum board	Delayed (CWFs)
5	11.1	0.090	10.77	Inside	8" Block with perlite and concrete filled + Insulation + Gypsum board	Delayed (CWFs)
6	7.8	0.129	10.87	Outside	Stucco + Insulation + 8" Block with perlite filled + Stud + Air + Gypsum board	Delayed (CWFs)
7	7.7	0.130	13.68	Outside	Stucco + Insulation + 8" Block with perlite and concrete filled + Stud + Air + Gypsum board	Delayed (CWFs)

Insulation Properties

In order to match the overall U-value (U_w) of each wall type with the high-mass materials in the 2001 IECC, the thickness of the insulation was adjusted (Table 6). As mentioned at the background, since the "quick" mode option does not use the specific wall layers but use overall U-values for the walls, there is no insulation layer property on #1 wall type on Table 6. The conductivity of the insulating material for simulations is the mineral wool/fiber based on the material library of DOE-2 BDL Summary (LBNL 1993) and the thickness and conductivity of the insulation is as follows. The thickness and conductivity of the insulation property is an artificial means of meeting the IECC requirements in the model and may be not physically appropriate for the massive walls.

Table 6. Insulation Layer Properties.

No	Thickness (ft)	Conductivity (Btu-ft/hr-ft2-F)	R-value (hr-ft2-F/Btu)
1	N/A	N/A	N/A
2	0.405	0.0270	15.0
3	0.291	"	10.8
4	0.130	"	4.8
5	0.214	"	7.9
6	0.008	"	0.3
7	0.090	"	3.3

RESULTS

Figure 3 shows the annual energy consumption from the DOE-2 simulations using DOE-2's Building Energy Performance Summary (BEPS) report. The number directly below the stacked bar refers to the wall number listed in Table 5. The value in parenthesis indicates the total energy use[13]. Figure 4 shows the total annual difference between the quick construction mode (#1) and the delayed construction modes (i.e., walls #2 to #7), which is presented to show the error that can occur when one mistakenly compares simulation methods in the DOE-2 program instead of thermal mass effects (i.e., the quick wall [i.e., ASHRAE Pre-calculated Weighting Factors], versus the Custom Weighting Factors). Figure 5 shows the correct comparison between a layered, lightweight wall (#2) and the walls containing different amounts of thermal mass (i.e., greater than 6 Btu/ft^2-°F) of heat-capacity at varying locations, all of which are simulated with DOE-2's Custom Weighting Factors.

[13] For example, the "1(92.9)" under the first stacked bar indicates wall type #1 and a total energy use of 92.9 mBtu/yr.

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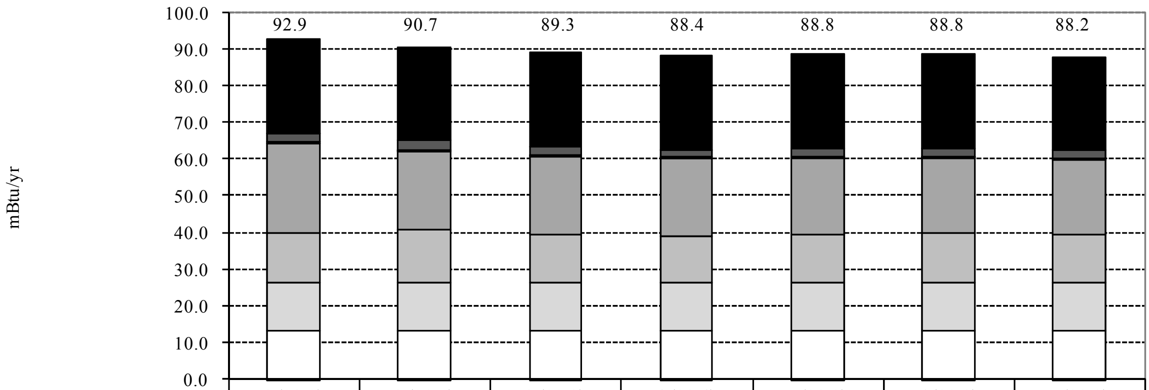


	1 (92.9)	2 (90.7)	3 (89.3)	4 (88.4)	5 (88.8)	6 (88.8)	7 (88.2)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.6	2.3	2.3	2.2	2.2	2.2	2.2
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	24.7	21.8	21.5	21.1	21.2	20.9	20.8
SPACE HEAT	13.5	14.5	13.4	13.0	13.3	13.6	13.1
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure 3: Total Annual Energy Use for Seven Wall Types with Thermostat Setback.

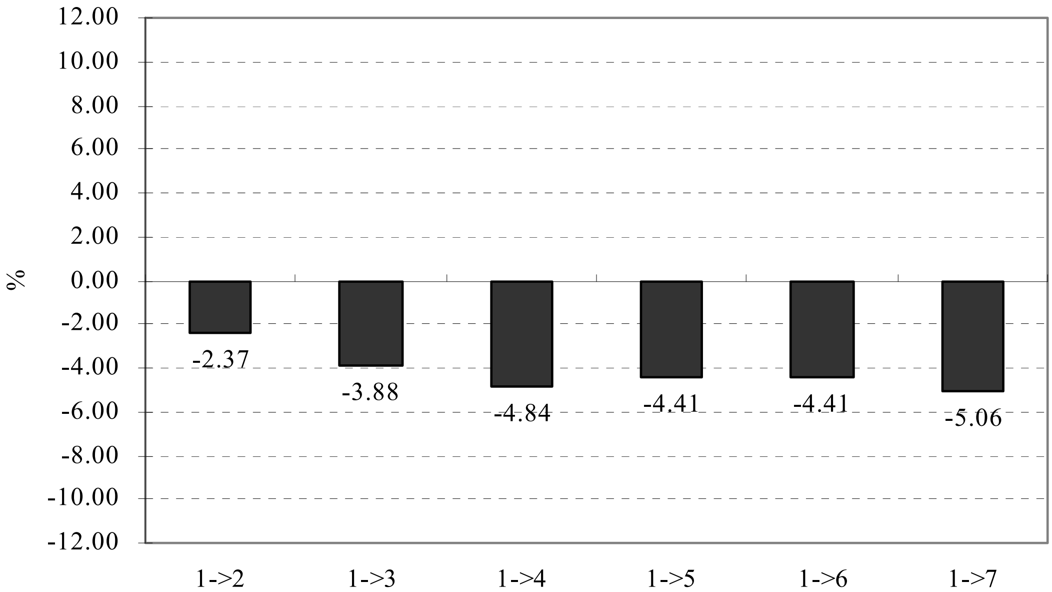


Figure 4: Change in Annual Total Energy Consumption from Quick Mode to Delayed Mode (Custom Weighting Factors) for Varying Amounts of Thermal Mass with Thermostat Setback.

In Figure 4 (with thermostat) and Figure 9 (without thermostat), which show the comparison of calculation methods, when the typical wood frame wall (#2) with the same U-value as the quick construction mode (#1) was simulated it was observed that the quick construction mode showed 2.4% more annual energy consumption (92.9 MBtu), versus the same simulation using a layered construction with a similar U-value (90.7 MBtu) for the simulations with the thermostatic setback (Figure 4). In Figure 9, the quick construction mode shows 1.16% more annual energy consumption (94.7 MBtu), versus the same simulation using a layered construction with a similar U-value (93.6 MBtu) for the simulations without the thermostatic setback. This indicated that simulations run with DOE-2's quick mode over-state the annual energy use when compared to simulation run with layered walls and roofs and Custom Weighting Factors. The reasons for this are complex, involving differences in the weighting factors and subroutines within the DOE-2 program. However, one of the primary observed results from the simulations (Kim 2006) show that the quick simulation (i.e., ASHRAE pre-calculated weighting factors) requires additional heating and cooling to maintain thermostat settings of the lightweight house because of the rapid cycling of the system when heating/cooling loads are light and the zone drifts in and out of the dead band because of the lack of thermal mass in the house. Hence, other values shown in Figure 4 should be viewed with caution since the differences in the simulation method are on the order of the differences in the energy use due to wall construction and thermal mass differences.

In Figure 5 to Figure 7 differences in the total annual energy consumption, cooling energy consumption, and heating energy consumption for lightweight (#2) and thermal mass walls (#3 to #7) are shown for walls simulated with DOE-2 CWFs, layered construction and thermostatic setback.

In Figure 8 to Figure 12 results are shown for the same configurations without a thermostatic setback. In these figures the following observations can be seen: 1) In Figure 5, it was found that all of the mass walls simulated showed an annual energy use less than that of the wood frame wall (#2), which would indicate that the U-values for the mass wall credits in Table 502.2.1.1.2 (1) and (2) of the 2001 IECC provided slightly more stringent annual energy use for the residence simulated in Houston, Texas.

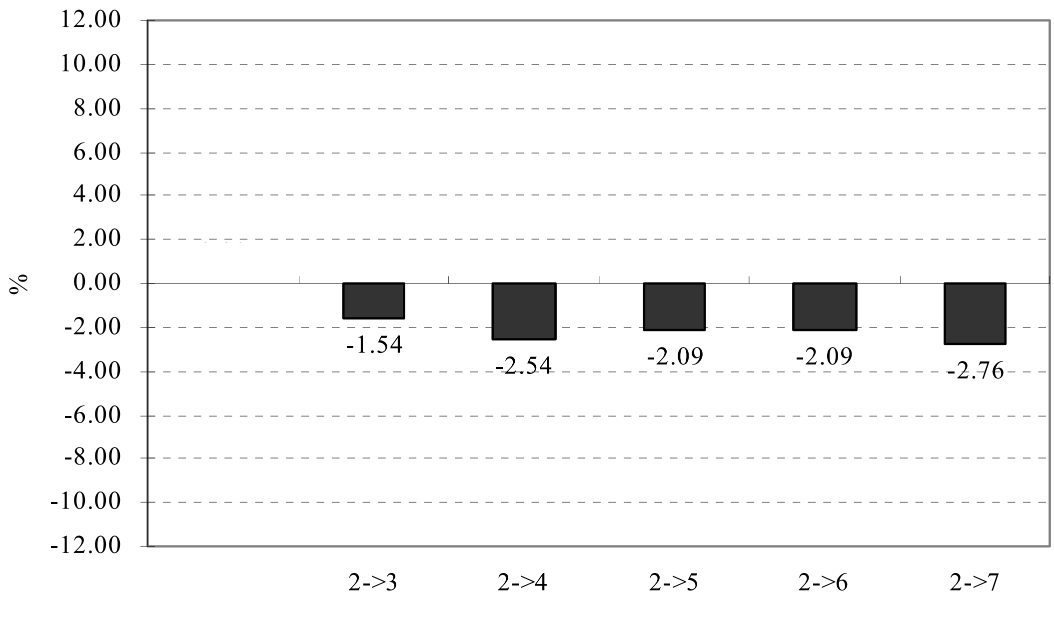


Figure 5: Change in Annual Total Energy Consumption for Varying Amounts of Thermal Mass using Delayed Mode (Custom Weighting Factors) with Thermostat Setback.

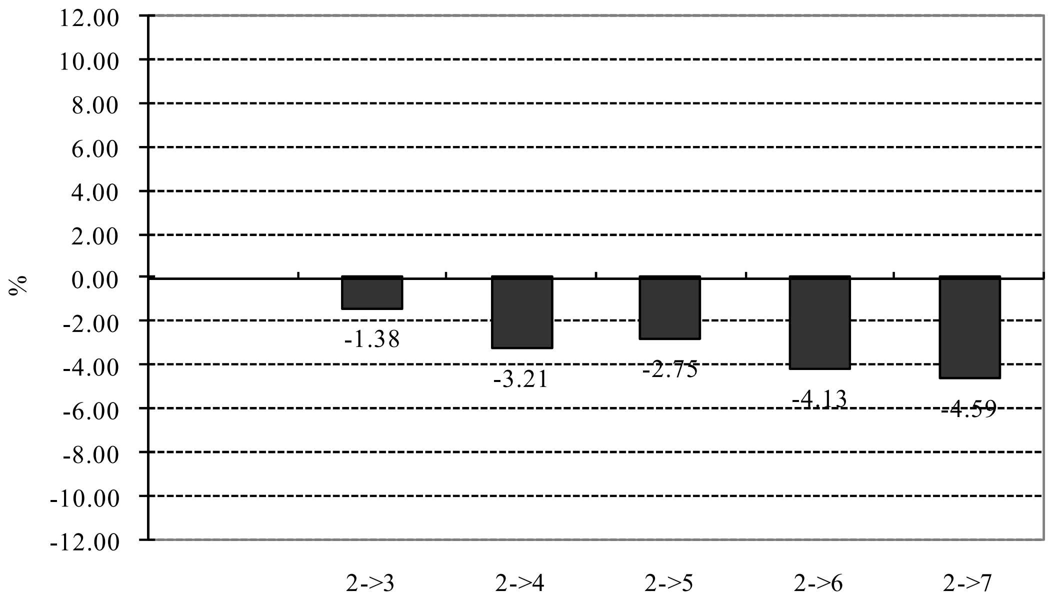


Figure 6: Change in Annual Cooling Energy Consumption for Varying Amounts of Thermal Mass using Delayed Mode (Custom Weighting Factors) with Thermostat Setback.

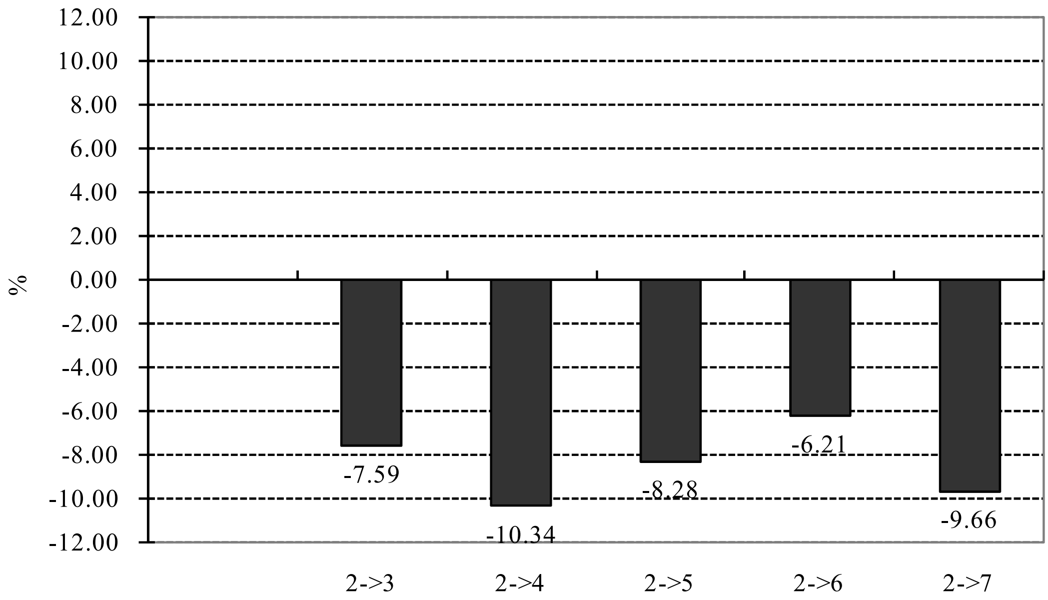
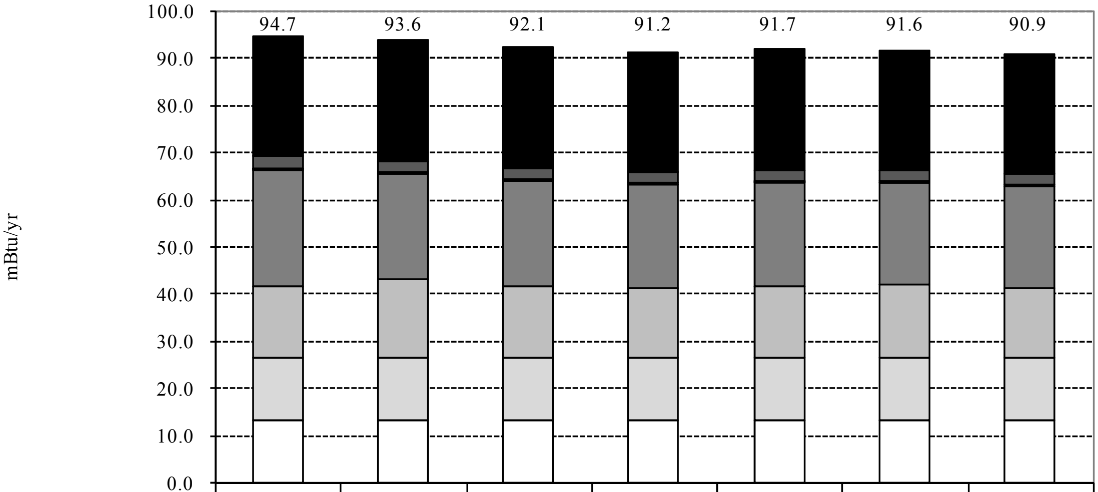


Figure 7: Change in Annual Heating Energy Consumption for Varying Amounts of Thermal Mass using Delayed Mode (Custom Weighting Factors) with Thermostat Setback.

2) In Figure 6 and Figure 7, the results show that the mass walls contributed substantially more to the heating energy savings (average 1.22 mBtu/year) than the cooling energy savings (average 0.70 mBtu/year).

3) In a similar fashion to the simulations with the thermostat setback, the results showed that all of the mass walls simulated without thermostatic setback showed an annual energy use less than that of the wood frame wall (#2) for the residence in Houston, Texas (Figure 10), with similar contributions for cooling and heating (Figure 11 and Figure 12).



	1 (94.7)	2 (93.6)	3 (92.1)	4 (91.2)	5 (91.7)	6 (91.6)	7 (90.9)
DOMHOT WATER	25.5	25.5	25.5	25.5	25.5	25.5	25.5
VENT FANS	2.6	2.4	2.4	2.3	2.3	2.3	2.3
PUMPS & MISC	0.2	0.2	0.2	0.2	0.2	0.2	0.2
SPACE COOL	24.9	22.5	22.3	21.9	22.1	21.8	21.6
SPACE HEAT	15.1	16.6	15.3	14.9	15.2	15.4	14.9
MISC EQUIPMT	13.2	13.2	13.2	13.2	13.2	13.2	13.2
AREA LIGHTS	13.2	13.2	13.2	13.2	13.2	13.2	13.2

Figure 8: Total Annual Energy Use for Seven Wall Types without Thermostat Setback.

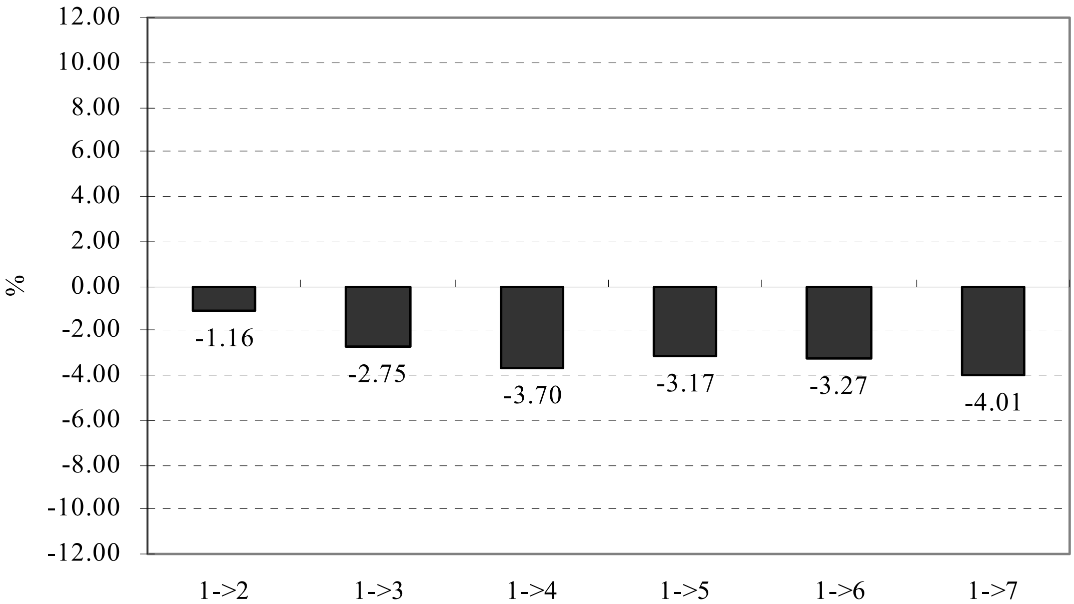


Figure 9: Change in Annual Total Energy Consumption from Quick Mode to Delayed Mode (Custom Weighting Factors) for Varying Amounts of Thermal Mass without Thermostat Setback.

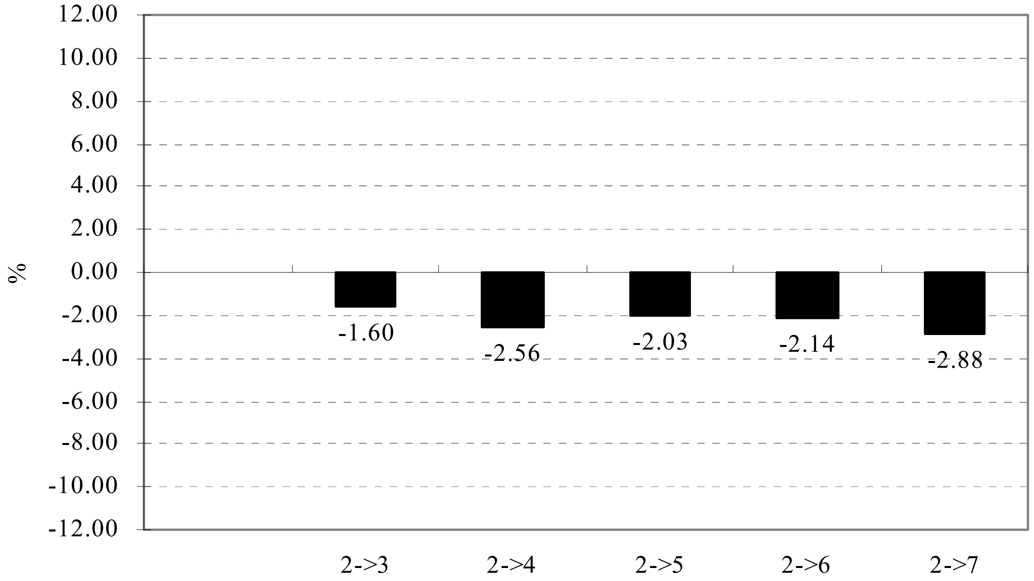


Figure 10: Change in Annual Total Energy Consumption for Varying Amounts of Thermal Mass Using Delayed Mode (Custom Weighting Factors) without Thermostat Setback.

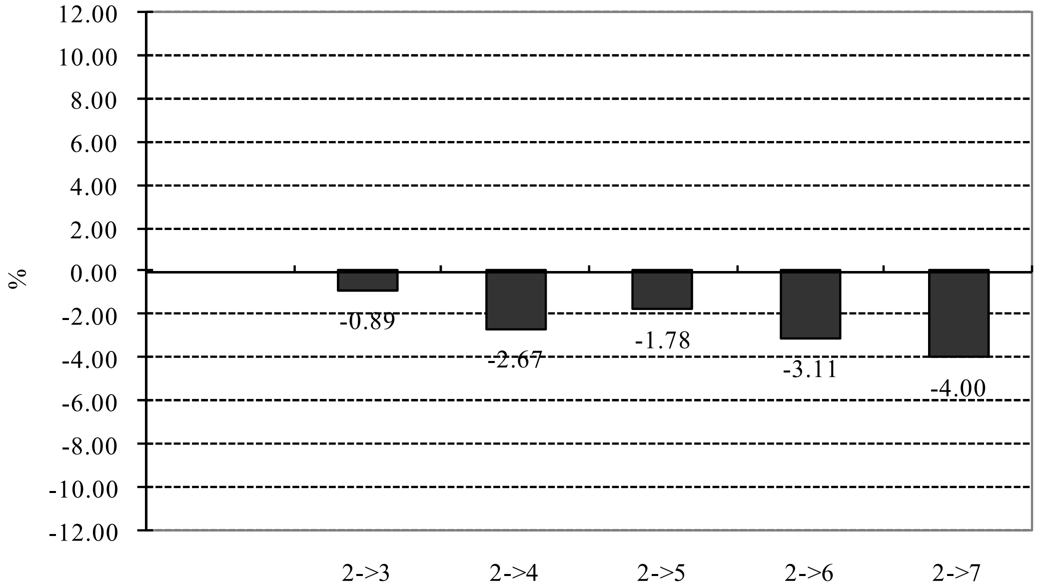


Figure 11: Change in Annual Cooling Energy Consumption for Varying Amounts of Thermal Mass Using Delayed Mode (Custom Weighting Factors) without Thermostat Setback.

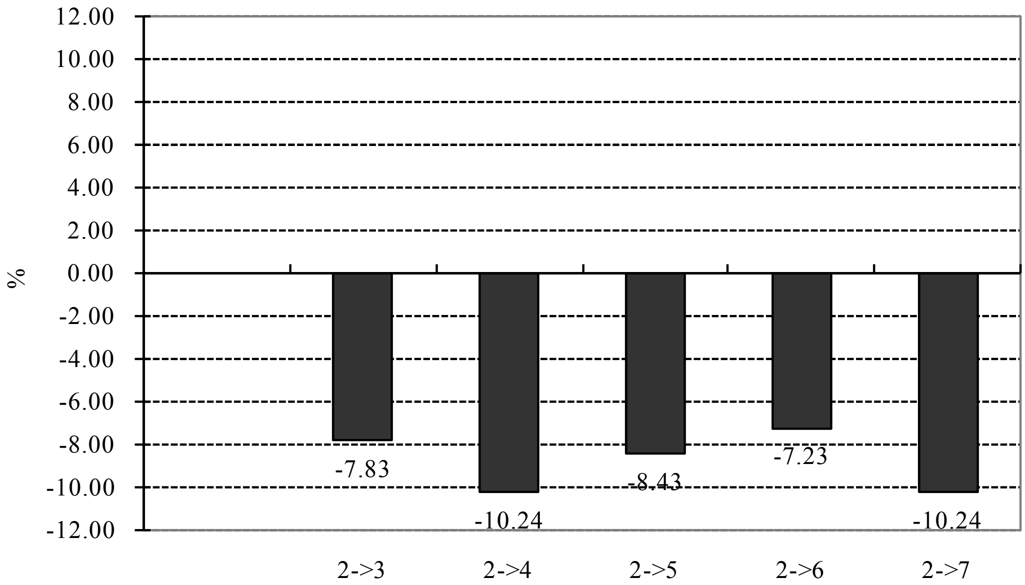


Figure 12: Change in Annual Heating Energy Consumption for Varying Amounts of Thermal Mass using Delayed Mode (Custom Weighting Factors) without Thermostat Setback.

4) A comparison of the annual energy use for the different wall types with and without thermostatic setback yielded some interesting findings. In Table 7, the simulated annual energy use for wall types #2 through #7 are shown for simulations with the thermostatic setback (column 2), and without thermostatic setback (column 3). Two different comparisons are also presented in columns 3 and 4. In column 4 the annual energy use for each wall type (without thermostatic setback) is compared against the same wall type with the thermostatic setback and shows a remarkably consistent 3% annual energy savings by using thermostatic setback, regardless of wall type.

In column 3 the annual energy use for each wall is compared against the annual energy use of wall type #2 simulated with thermostatic set back. This comparison is presented since it was felt that it compares the annual energy use of a lightweight wall, simulated with thermostatic setback, against the energy use of the different wall types simulated without thermostatic setback. It reveals that as thermal mass is added to the different walls the benefits of the thermostatic setback diminish, which implies that the thermal mass tables might need to be reconsidered for applications without thermostatic setback, since it appears from results of the simulation that the benefits disappear as one increases the thermal mass in the walls.

Table 7: Comparisons of Annual Energy Use, by Wall Type for a Residence with and without Thermostatic Setback.

Wall Number	Annual Energy Use w/ Thermostat Setback (MBtu/yr)	Annual Energy Use w/o Thermostat Setback (MBtu/yr)	Wall Type w/o Thermostat Setback vs Wall Type #2 w/ Thermostat Setback (% Change)	Wall Type w/o Thermostat Setback vs the Same Wall Type w/ Thermostat Setback (% Change)
#2	90.7	93.6	+3.20%	+3.20%
#3	89.3	92.1	+1.54%	+3.14%
#4	88.4	91.2	+0.55%	+3.17%
#5	88.8	91.7	+1.11%	+3.27%
#6	88.8	91.6	+0.99%	+3.15%
#7	88.2	90.9	+0.22%	+3.06%

SUMMARY

It was found that 1) the thermal mass credits in the 2001 IECC yield more stringent constructions than light weight walls, 2) adding thermal mass to the walls diminishes the effect of the thermostat setback, and 3) simulation instruction need to be included in the IECC to properly account for the various types of thermal mass walls.

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